Effect of Radiative Transfer on the Vertical Distribution of Temperature in the Troposphere

著者	Yamamoto Giichi
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By Giichi YAMAMOTO

Institute of Geophysics, Faculty of Science, Tôhoku University

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1. Introduction

Until some time ago the effect of radiative transfer on the vertical distribution of temperature in the troposphere was much underestimated by the meteorologists than it ought to be. For instance, according to BRUNT [1] the transfer of heat by infra-red radiation was estimated to be 1/10∼1/100 of the turbulent transfer and accordingly was considered to be negligible. It was also disregarded in discussing the transfer of heat near the ground. However, recently the rôle of the radiation on the problems of the tropospheric temperature changes was emphasized by DEACON [2] and ROBINSON [6]. It was also noticed by ELSASSER [3] that the radiative cooling of the troposphere will act as the stabilizing factor in the troposphere. In this paper it is shown that the actual lapse-rate of temperature in clear skies which is generally smaller than the dry adiabatic lapse-rate is the consequence of the balance of the eddy transfer and the radiative transfer. It is also shown that near the ground the temperature changes due to radiation are sufficiently large to account for the observed temperature changes.

2. The Effect of Radiation on the Lapse-Rate of Temperature in the Troposphere

It was shown by BRUNT [1] that the vertical transfer of heat by turbulence is given by

$$\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left\{K\rho\left(\frac{\partial T}{\partial z} + \Gamma\right)\right\}, \quad (1)$$

where T=the temperature of the air at level z

ρ=the density of the air at level z

K=the eddy diffusivity

Γ=the dry adiabatic lapse-rate

t=the time

If we consider, in addition to the eddy flux, the radiative fluxes due to infra-rad radiation and solar radiation, the equation of heat transfer will become as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left\{K\rho c_p\left(\frac{\partial T}{\partial z} + \Gamma\right)\right\} - \frac{\partial F_1}{\partial z} + \frac{\partial F_2}{\partial z}, \quad (2)$$

where c_p is the specific heat of air at constant pressure, F_1 is the infra-red net flux which is directed upwards and F_2 is the mean effective solar radiation per day which is directed downwards. In the case of steady state, we have

$$-K\rho c_p\left(\frac{\partial T}{\partial z} + \Gamma\right) + F_1 - F_2 = \text{const.} \quad (3)$$

Equation (3) means that the troposphere is neither in convective nor in radiative equilibrium, but in, so to say, radiato-convctive equilibrium. If we designate the surface values of the variable quantities in (3) by adding suffix 0 to the variables then we have

$$K\rho c_p\left(\frac{\partial T}{\partial z} + \Gamma\right) = K_0\rho_0 c_p\left\{\left(\frac{\partial T}{\partial z}\right)_0 + \Gamma\right\} + \{F_1 - (F_1)_0\} - \{F_2 - (F_2)_0\}. \quad (4)$$

By the recent works of LONDON [4], YAMAMOTO [8] and YAMAMOTO and ONISHI [9], we can see that $\{F_1 - (F_1)_0\} - \{F_2 - (F_2)_0\}$ takes positive values throughout the troposphere, and $K_0\rho_0 c_p\{(\partial T/\partial z)_0 + \Gamma\}$ is also positive in general case. Hence from equation (4) it will be said that the normal lapse-rate in clear skies which is generally smaller than the dry adiabatic lapse-rate is due to the radiato-convective equilibrium of the troposphere. Regrettably the values of the eddy diffusivity K are not so well known with regard to height as to be able to infer the normal values of the lapse-rate in the troposphere which satisfy equation (4).

However, if we assume the validity of equation (4), we can inversely use the equation to compute the vertical distribution of K for tropospheric conditions in which the values of F_1, F_2 and $\partial T/\partial z$ are known. The values of F_1 and F_2 were most fully investigated by LONDON [4] for model atmospheres during March, northern hemisphere, so that the computation of K was carried out on LONDON's model atmospheres in clear skies, assuming that $K_0 = 10^5$ cm^2 sec^{-1} at each case. Also the Austausch coefficient $A\,(=\rho c_p K)$ was computed. The results of computation were shown in table 1 and fig. 1 and 2. Fig. 1 shows that the computed values of K generally increase with height at each latitude belt. In the lower troposphere below 3 km K increases linearly with height, and in the middle troposphere the rate of increase of K with height becomes rapid, until K reaches maximum in the upper troposphere, and in the uppermost layer immediately below tropopause K tends to decrease at each latitude belt. The vertical distribution of A (fig. 2) also shows similar tendency as K. However, in this case the decrease of A with height begins at lower altitude than that of K, and it is more marked in the upper troposphere than in the case of K.

Table 1. Vertical distribution of eddy diffusivity K and Austausch coefficient A, during March, northern hemisphere, in clear skies.
z: km, $\partial T/\partial z+\Gamma$: °C. cm^{-1}, $F_1-(F_1)_0$ and $F_2-(F_2)_0$: cal. cm.$^{-2}$ min.$^{-1}$
K: cm.^{2} sec.$^{-1}$ A: cal. cm.$^{-1}$ sec.$^{-1}$ °C^{-1}

0-10° N						10-20° N					
z	$\partial T/\partial z+\Gamma$ $\times 10^{-5}$	$F_1-(F_1)_0$ $\times 10^{-1}$	$F_2-(F_2)_0$ $\times 10^{-2}$	K $\times 10^5$	A	z	$\partial T/\partial z+\Gamma$ $\times 10^{-5}$	$F_1-(F_1)_0$ $\times 10^{-1}$	$F_2-(F_2)_0$ $\times 10^{-2}$	K $\times 10^5$	A
0	4.96	0	0	1.00	27.9	0	4.56	0	0	1.00	28.6
1	5.11	0.25	1.33	1.21	30.8	1	4.56	0.31	1.26	1.36	35.4
2	5.11	0.49	2.45	1.52	35.0	2	4.51	0.56	2.43	1.75	40.7
3	4.66	0.68	3.43	2.19	45.2	3	4.26	0.79	3.52	2.28	47.6
4	4.21	0.88	4.31	2.70	50.6	4	4.16	1.01	4.41	2.82	54.2
5	4.21	1.07	5.13	3.22	54.8	5	4.26	1.25	5.10	3.44	59.5
6	3.86	1.27	5.85	4.19	65.4	6	3.56	1.49	5.72	5.12	79.8
7	3.31	1.45	6.48	5.80	82.0	7	2.96	1.69	6.26	7.46	104
8	3.26	1.63	7.02	7.06	89.9	8	2.96	1.87	6.70	8.93	111
9	3.16	1.80	7.49	8.80	99.2	9	2.96	2.01	7.05	10.4	118
10	2.16	1.95	7.88	14.9	153.5	10	2.56	2.13	7.32	14.1	142
11	1.26	2.07	8.21	31.0	275	11	2.26	2.22	7.53	18.7	166
12	1.31	2.19	8.46	34.9	277	12	2.41	2.30	7.69	20.2	159
13	2.31	2.28	8.85	29.2	204	13	3.31	2.36	7.79	17.1	119
14	3.21	2.35	8.74	19.9	118	14	4.36	2.40	7.86	15.9	92
15	3.26	2.42	8.81	24.0	121	15	4.36	2.45	7.91	20.5	93
16	3.36	2.46	8.85	27.6	132	16	4.36	2.45	7.95	19.4	93

20-30° N

z	$\partial T/\partial z+\Gamma$ $\times 10^{-5}$	$F_1-(F_1)_0$ $\times 10^{-1}$	$F_2-(F_2)_0$ $\times 10^{-2}$	K $\times 10^5$	A
0	4.06	0	0	1.00	28.8
1	3.86	0.30	1.27	1.44	37.7
2	3.96	0.58	2.35	1.89	43.0
3	4.21	0.84	3.19	2.29	48.3
4	4.16	1.03	3.89	2.83	53.7
5	4.21	1.20	4.52	3.28	57.5
6	3.56	1.38	5.06	4.74	73.9
7	2.76	1.56	5.52	7.28	103
8	2.61	1.73	5.89	9.41	117
9	2.46	1.88	6.19	11.8	132
10	2.91	2.00	6.41	12.8	129
11	3.46	2.08	6.56	11.5	102
12	3.36	2.13	6.68	13.9	107
13	4.81	2.16	6.75	10.9	76
14	6.31	2.19	6.79	9.7	58
15	6.16	2.22	6.84	12.0	61
16	6.47	2.25	6.88	12.2	60

30-40° N

z	$\partial T/\partial z+\Gamma$ $\times 10^{-5}$	$F_1-(F_1)_0$ $\times 10^{-1}$	$F_2-(F_2)_0$ $\times 10^{-2}$	K $\times 10^5$	A
0	5.86	0	0	1.00	29.8
1	5.56	0.23	0.81	1.33	35.8
2	4.86	0.46	1.56	1.91	46.3
3	4.51	0.66	2.33	2.52	54.4
4	4.16	0.85	2.88	3.28	64.6
5	3.41	1.04	3.35	4.89	85.6
6	2.56	1.22	3.84	7.51	123
7	2.06	1.37	4.25	11.6	162
8	2.26	1.50	4.53	12.3	154
9	3.11	1.59	4.71	10.5	116
10	4.56	1.65	4.83	8.2	81
11	5.61	1.70	4.91	8.2	67
12	6.26	1.72	4.97	8.4	60
13	6.91	1.74	5.03	8.2	55

40-50° N

z	$\partial T/\partial z+\Gamma$ $\times 10^{-5}$	$F_1-(F_1)_0$ $\times 10^{-1}$	$F_2-(F_2)_0$ $\times 10^{-2}$	K $\times 10^5$	A
0	6.86	0	0	1.00	30.7
1	6.36	0.19	0.56	1.35	34.6
2	5.51	0.37	1.14	1.88	46.0
3	4.36	0.58	1.79	2.94	63.5
4	3.21	0.79	2.34	4.76	94.8
5	2.86	0.99	2.76	6.48	115
6	2.86	1.12	3.10	7.51	121
7	2.96	1.23	3.36	8.57	121
8	3.61	1.32	3.53	8.25	103
9	3.91	1.39	3.63	8.85	98
10	6.11	1.42	3.70	6.25	63
11	8.71	1.45	3.76	5.33	45

50-60° N

z	$\partial T/\partial z+\Gamma$ $\times 10^{-5}$	$F_1-(F_1)_0$ $\times 10^{-1}$	$F_2-(F_2)_0$ $\times 10^{-2}$	K $\times 10^5$	A
0	7.36	0	0	1.00	31.6
1	6.96	0.16	0.45	1.28	36.2
2	5.96	0.32	0.86	1.81	46.7
3	4.51	0.49	1.26	2.98	65.1
4	3.56	0.68	1.62	4.50	89.6
5	3.76	0.83	1.90	5.08	90.2
6	4.06	0.94	2.11	5.51	87.2
7	4.46	1.02	2.26	5.79	82.0
8	4.86	1.10	2.37	6.20	77.4
9	4.96	1.14	2.45	6.98	76.4
10	7.66	1.17	2.52	5.26	50.5

60-70° N

z	$\partial T/\partial z+\Gamma$ $\times 10^{-5}$	$F_1-(F_1)_0$ $\times 10^{-1}$	$F_2-(F_2)_0$ $\times 10^{-2}$	K $\times 10^5$	A
0	7.16	0	0	1.00	32.8
1	7.01	0.12	0.24	1.23	35.8
2	6.71	0.25	0.49	1.56	40.2
3	5.36	0.42	0.73	2.40	54.7
4	4.51	0.54	0.94	3.45	68.7
5	5.26	0.64	1.08	3.42	61.5
6	5.86	0.70	1.19	3.52	56.6
7	6.21	0.75	1.27	3.99	54.5
8	6.41	0.80	1.35	4.41	54.0
9	6.46	0.83	1.41	5.12	54.1
10	8.51	0.86	1.46	4.45	41.6

3. The Radiative Temperature Change near the Ground

DEACON and ROBINSON have emphasized the importance of the radiative temperature change near the ground. DEACON's computations of the radiative flux were carried out on an example at night, which has demonstrated that the night cooling of air can be fully explained by the radiative cooling. ROBINSON's computations were carried out on three examples at midday, evening and early night. According to his computations the radiative heating at midday or the radiative cooling at night far exceeds the observed rate

Fig. 1 Vertical distribution of eddy diffusivity K.

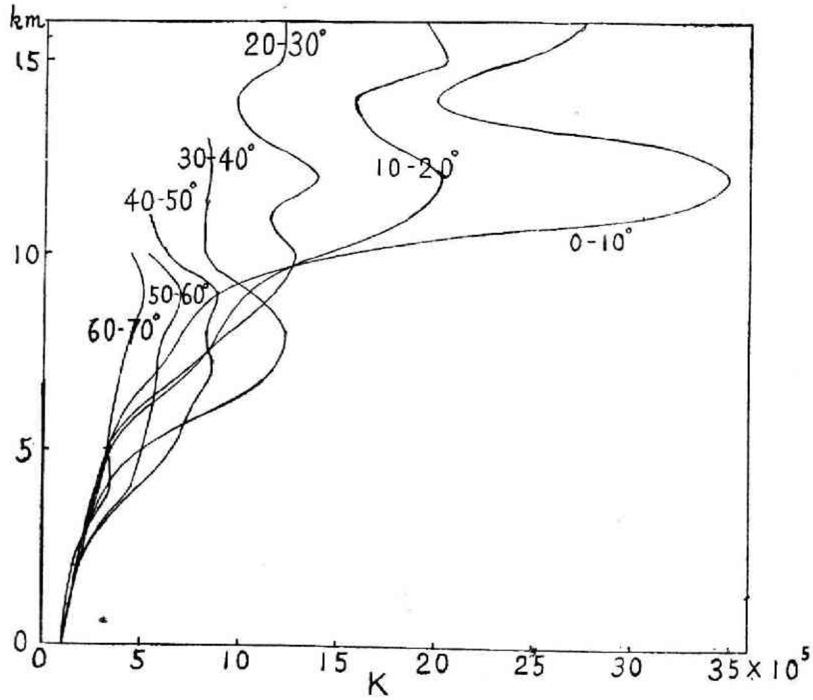
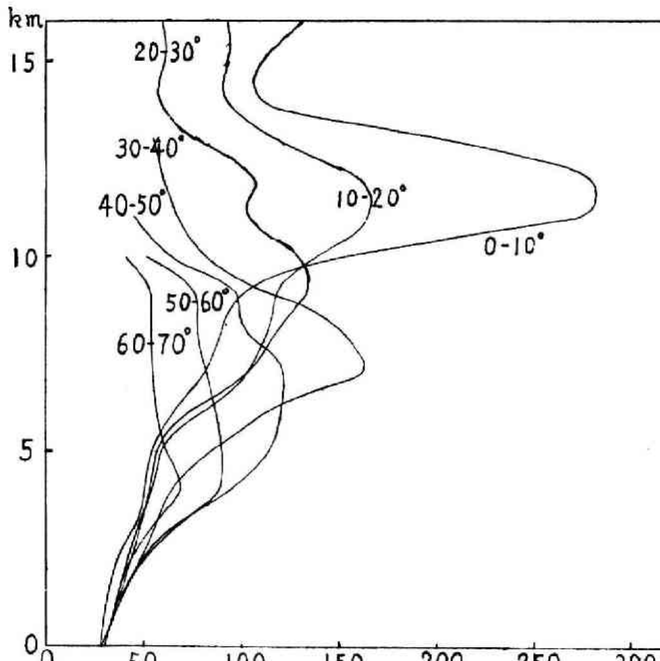


Fig. 2 Vertical distribution of Austausch coefficient A.



of temperature change, so that it may be likely that the radiative heating at midday or the cooling at night is almost balanced by convection. Then, convection or turbulent transfer will to cool the air near the ground at midday when the earth is heated by solar radiation and to heat the air at night when the earth surface is cooling. This conclusion seems to be somewhat curious. To investigate more fully the rôle of radiative transfer near the ground, it is necessary to carry out computations of the radiative flux near the ground on more numerous examples.

Now to be able to compute the radiative flux near the ground, the complete knowledge of the vertical distributions of temperature and humidity including the surface values are necessary. Although many observations have been carried out on the vertical distributions of temperature and humidity, such complete observations are rare. Recent observations of PASQUILL [5] are one of these few, in which the surface temperature was measured by a spirit thermometer lying on the ground. Although the true surface temperature is difficult to measure, it has been shown by ROBINSON [7] that the radiative temperature of ground covered by short grass is indicated by a spirit thermometer lying on the ground with the following degree of approximation:

$T_r = T_s + 0.25 \pm 0.6°C$ at night and at daytime with weak insolation

$T_r = T_s - 0.5 \pm 1.2°C$ at daytime with strong insolation

where T_r is the radiative surface temperature and T_s is the reading of the surface thermometer.

PASQUILL's observations extend up to 2 m high, so that data of temperature and humidity at higher level are desirable to carry out reliable computations of the radiative flux. Thus the values of temperature and humidity at 10 m high were assumed by extrapolating his observations. Also surface values of the absolute humidity which were lacking in his observations were assumed. The complete data thus supplemented were obtained on No. 6-10, and 15-19 of table 2 of PASQULL's paper and were shown in table 2.

Table 2. Vertical distribution of tempertaure and reduced path

	z (cm)	T (°K)	u (g cm^{-2})		z (cm)	T (°K)	u (g cm^{-2})
No. 6	0	288.96	0	No. 9	0	280.71	0
10^h33^m	25	285.04	0.000168	17^h30^m	25	283.47	0.000156
	50	284.67	0.000331		50	283.94	0.000309
	100	284.35	0.000647		100	284.46	0.000609
	150	284.20	0.000956		150	284.72	0.000905
	200	284.10	0.001261		200	284.88	0.001198
	1000	283.66	0.005946		1000	285.94	0.005813
No. 7	0	290.56	0	No. 10	0	279.11	0
12^h30^m	25	285.53	0.000170	19^h30^m	25	281.68	0.000197
	50	286.13	0.000334		50	281.94	0.000393
	100	285.77	0.000649		100	282.23	0.000781
	150	285.60	0.000955		150	282.38	0.001167
	200	285.49	0.001256		200	282.49	0.001551
	1000	284.94	0.005816		1000	283.16	0.007641
No. 8	0	286.60	0	No. 15	0	287.06	0
15^h30^m	25	286.58	0.000163	09^h38^m	25	282.65	0.000137
	50	286.59	0.000324		50	282.43	0.000267
	100	286.60	0.000638		100	282.17	0.000517
	150	286.60	0.000945		150	282.11	0.000757
	200	286.60	0.001249		200	281.99	0.000992
	1000	286.60	0.006049		1000	281.49	0.004562

	z (cm)	T (°K)	u (g cm^{-2})		z (cm)	T (°K)	u (g cm^{-2})
No. 16 11h30m	0	290.66	0	No. 18 16h30m	0	284.83	0
	25	285.35	0.000157		25	284.83	0.000141
	50	285.04	0.000307		50	284 83	0.000277
	100	284.66	0.000591		100	284.83	0.000540
	150	284.52	0.000865		150	284.83	0.000796
	200	284.38	0.001135		200	284.83	0.001048
	1000	283.61	0.005235		1000	284.83	0.004908
No. 17 14h30m	0	288.96	0	No. 19 18h30m	0	277.21	0
	25	286.74	0.000151		25	279.35	0.000119
	50	286.47	0.000296		50	279.64	0.000236
	100	286.24	0.000570		100	279.99	0.000466
	150	286.10	0.000832		150	280.22	0.000692
	200	285.99	0.001090		200	280.38	0.000916
	1000	285.41	0.005020		1000	281.33	0.004416

Now the differences of net flux at each 50 cm interval from the ground up to 2 m high were computed using the radiation chart developed by the author [8]. In this computation the CO_2 correction was neglected, because CO_2 contents in each 50 cm interval are nearly equal and the effect of CO_2 will be cancelled in taking flux divergence. The obtained flux divergences were expressed by the temperature change per hour and were shown in table 3. In table 3 are also shown the observed temperature changes per hour.

Tabel 3 Computed radiative temperature change and observed temperature change as functions of height.

	Z (cm)	A Mean observed temperature change $\left(\frac{\Delta T}{\Delta t}\right)$ obs (°C hour^{-1})	B Mean radiative temperature change $\left(\frac{\Delta T}{\Delta t}\right)$ rad (°C hour^{-1})	A-B
No. 6-7	0- 50	0.76	3.19	-2.43
	50-100	0.72	2.95	-2.23
	100-150	0.68	2.50	-1.82
	150-200	0.66	1.89	-1.23
No. 7-8	0- 50	-0.28	1.58	-1.86
	50-100	+0.22	1.53	-1.31
	100-150	+0.31	1.33	-1.02
	150-200	+0.35	0.98	-0.63
No. 8-9	0- 50	-1.96	-0.80	-1.16
	50-100	-1.20	-0.96	-0.24
	100-150	-1.01	-0.89	-0.12
	150-200	-0.90	-0.70	-0.20
No. 9-10	0- 50	-0.87	-1.74	+0.87
	50-100	-1.06	-1.78	+0.72
	100-150	-1.15	-1.47	+0.32
	150-200	-1.19	-1.18	-0.01

	Z (cm)	A Mean observed temperature change $\left(\frac{\Delta T}{\Delta t}\right)$ obs (°C hour^{-1})	B Mean radiative temperature change $\left(\frac{\Delta T}{\Delta t}\right)$ rad (°C hour^{-1})	A-B
No. 15-16	0- 50	1.56	3.54	-1.98
	50-100	1.36	3.10	-1.65
	100-150	1.31	2.49	-1.18
	150-200	1.28	1.97	-0.69
No. 16-17	0- 50	0.12	2.62	-2.50
	50-100	0.50	2.38	-1.88
	100-150	0.53	1.96	-1.43
	150-200	0.53	1.49	-0.96
No. 17-18	0- 50	-1.28	0.78	-2.06
	50-100	-0.77	0.70	-1.47
	100-150	-0.68	0.52	-1.20
	150-200	-0.61	0.39	-1.00
No. 18-19	0- 50	3.09	-0.61	-2.48
	50-100	-2.51	-0.59	-1.92
	100-150	-2.37	-0.54	-1.38
	150-200	-2.27	-0.53	-1.74

No. 6 : 10h33m
No. 7 : 12h30m
No. 8 : 15h30m
No. 9 : 17h30m
No. 10 : 19h30m

No. 15 : 9h38m
No. 16 : 11h30m
No. 17 : 14h30m
No. 18 : 16h30m
No. 19 : 18h30m

It will be seen from the table that the radiative heating at midday far exceeds the observed temperature change at corresponding time. On the other hand the radiative cooling at night is not necessarily so, that is, at No. 9-10, the radiative cooling is larger than the actual temperature change, while at No. 18-19 the contrary is the case. And at evening the radiative tempefature change is zero. In the table are also shown the difference of the observed temperature change and the radiation temperature change, which will correspond to the turbulent temperature change. Table 3 shows that the turbulent temperature change is negative at midday, that is, it means cooling. The curious conclusion of ROBINSON was thus not removed by the present computation. There is one way of thinking to escape from this curious conclusion. As the wind was blowing with 2-3 m/sec during the observations, the observed temperature change represents that of the average of considerable quantity of air, while the computed radiative temperature change depends mostly upon the surface temperature of a spot. If we assume that the mean surface temperature of some area around the spot is smaller than the surface temperature of the spot at midday, then the radiative heating will be diminished and there may be a possibility that the above conclusion will be remedied.

Finally, from table 3 we can see that the radiative heating at midday and the radiative cooling at night both decrease with height.

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